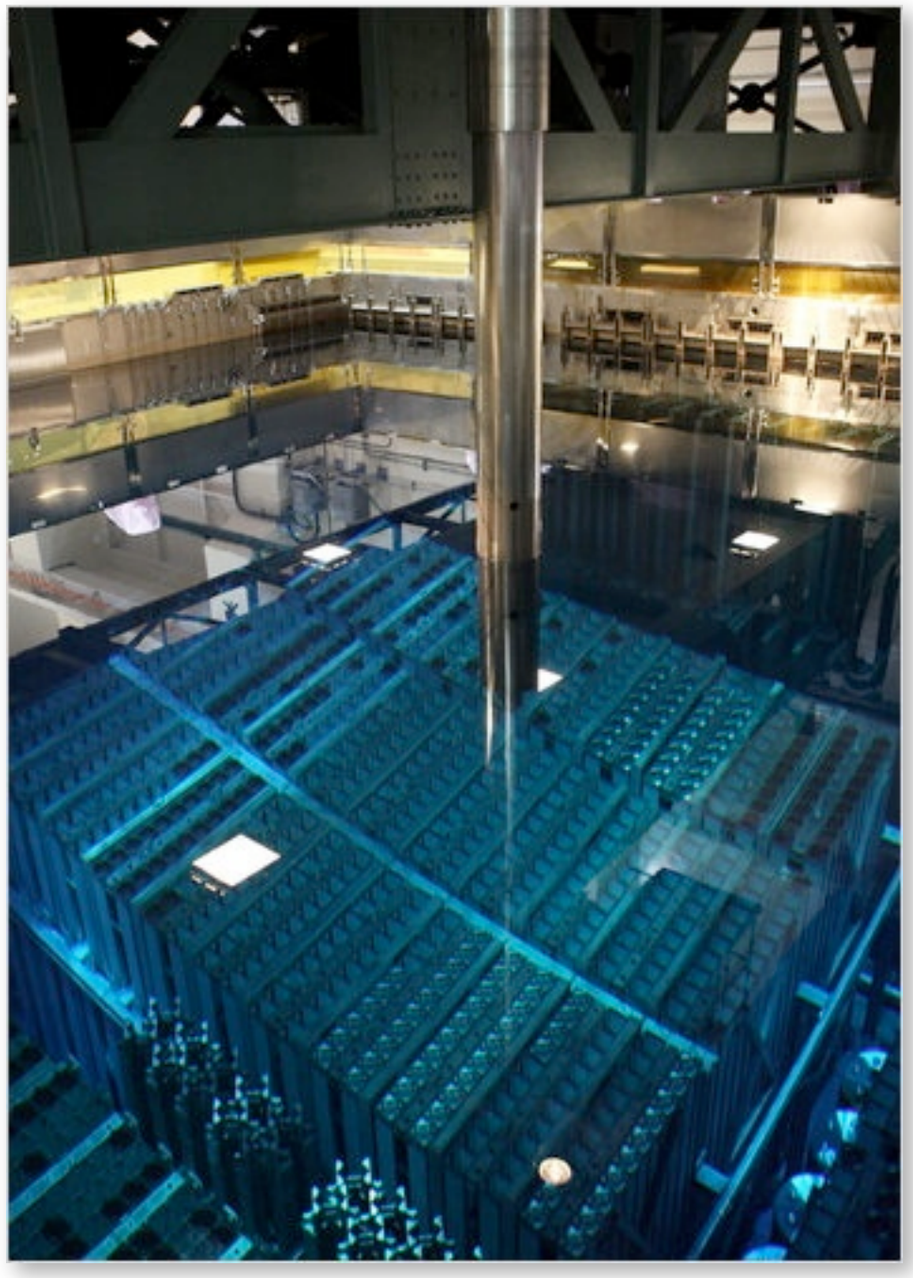
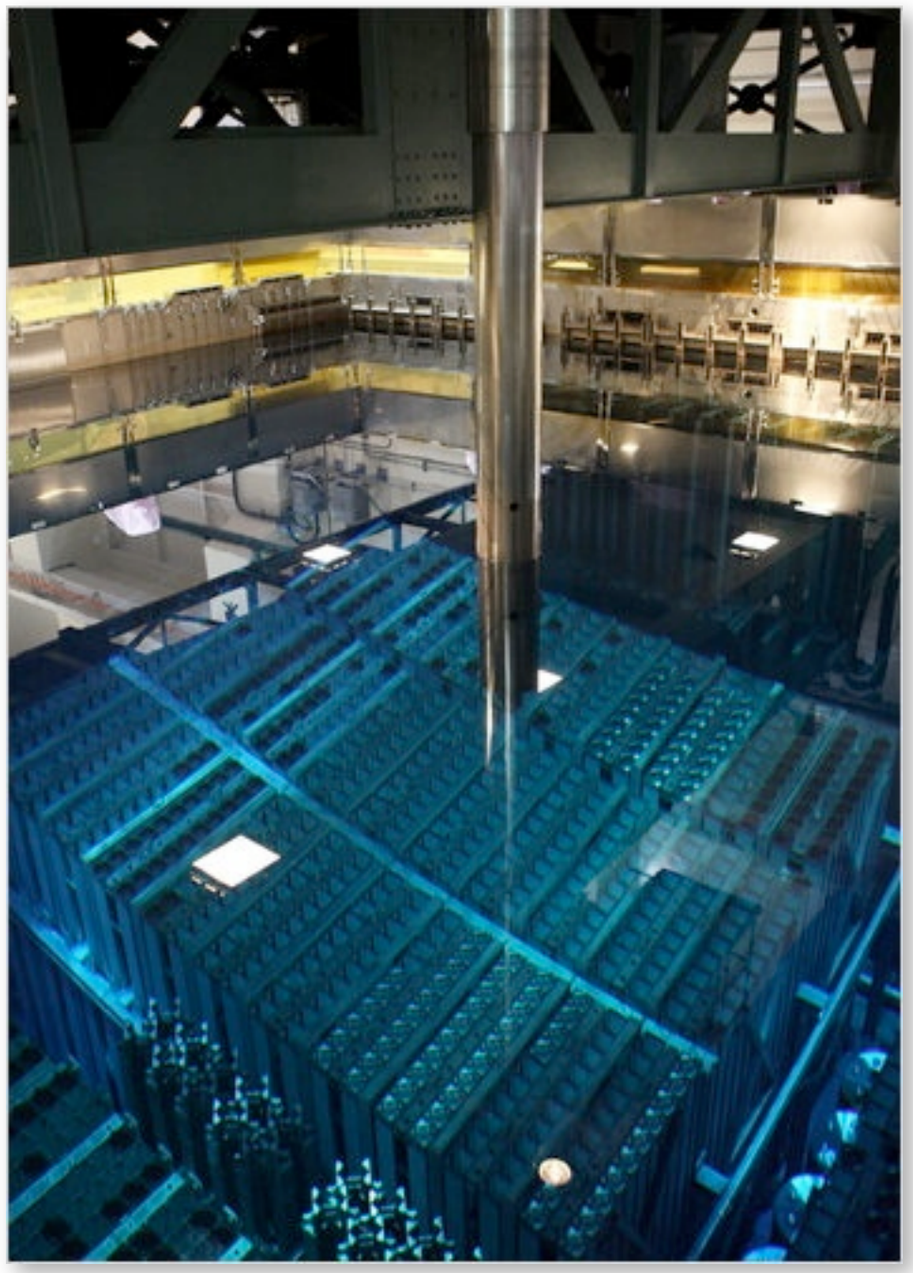
Fukushima: What We All Should Know about Radiation



Peter N. Saeta, Harvey Mudd College Physics, 25 March 2011

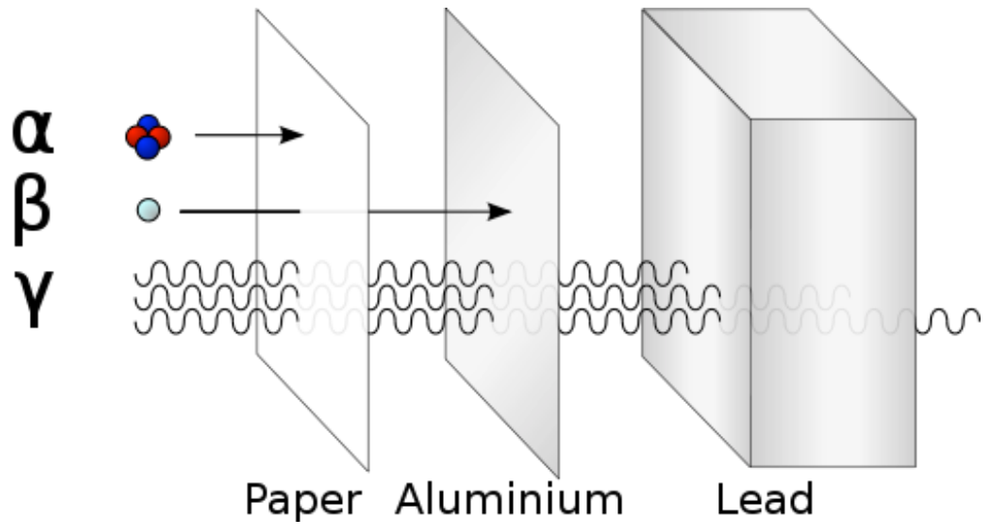
Outline

- Radioactivity: what is it, what causes it, and what's a half life?
- How does ionizing radiation interact with biological tissue?
- How does a reactor work and what are typical levels of radioactivity?
- What happened at Three Mile Island, Chernobyl, and Fukushima?
- Which kills more people, cars, planes, coal, oil, wind, or nuclear power?



What is radioactivity?

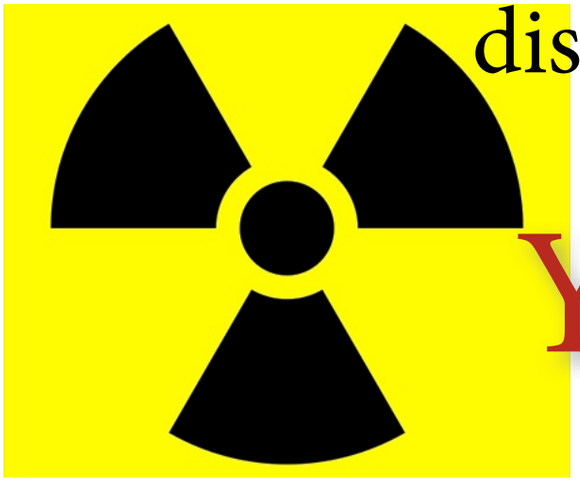
- Emission of one or more energetic particles from a nucleus
  - alpha (α) particle: helium nucleus
  - beta (β) particle: electron or positron
  - gamma (γ): high-energy light
  - neutron (n)
- Energetic enough to break atomic bonds (ionize)



http://wikipedia.org/

What causes radioactivity?

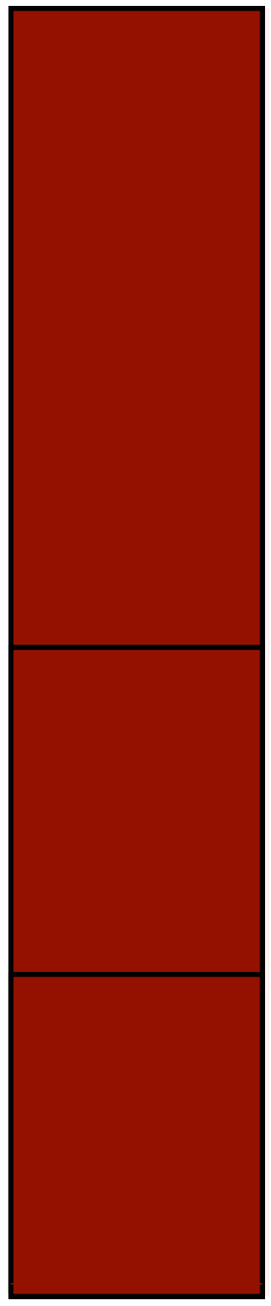
- Unstable nuclei can lower their energy by falling apart
- A (meta)stable nucleus absorbs a neutron and becomes unstable
  - C^{14} is made when cosmic rays (very energetic particles) collide with atmospheric nitrogen
    - In a typical human, 3000 carbon atoms disintegrate *per second*



You are radioactive!

What's a half life?

- Iodine-131 (I^{131}) has a half-life of 8 days
- If I have 1024 I^{131} nuclei in a jar, 8 days later I will have about 512
- After 16 days I will have about 256
- After 80 days, only 1 is left
    - Japanese near Fukushima should ingest nonradioactive potassium iodide to "saturate" their thyroid glands so radioactive iodine won't accumulate there



Quantities of radiation

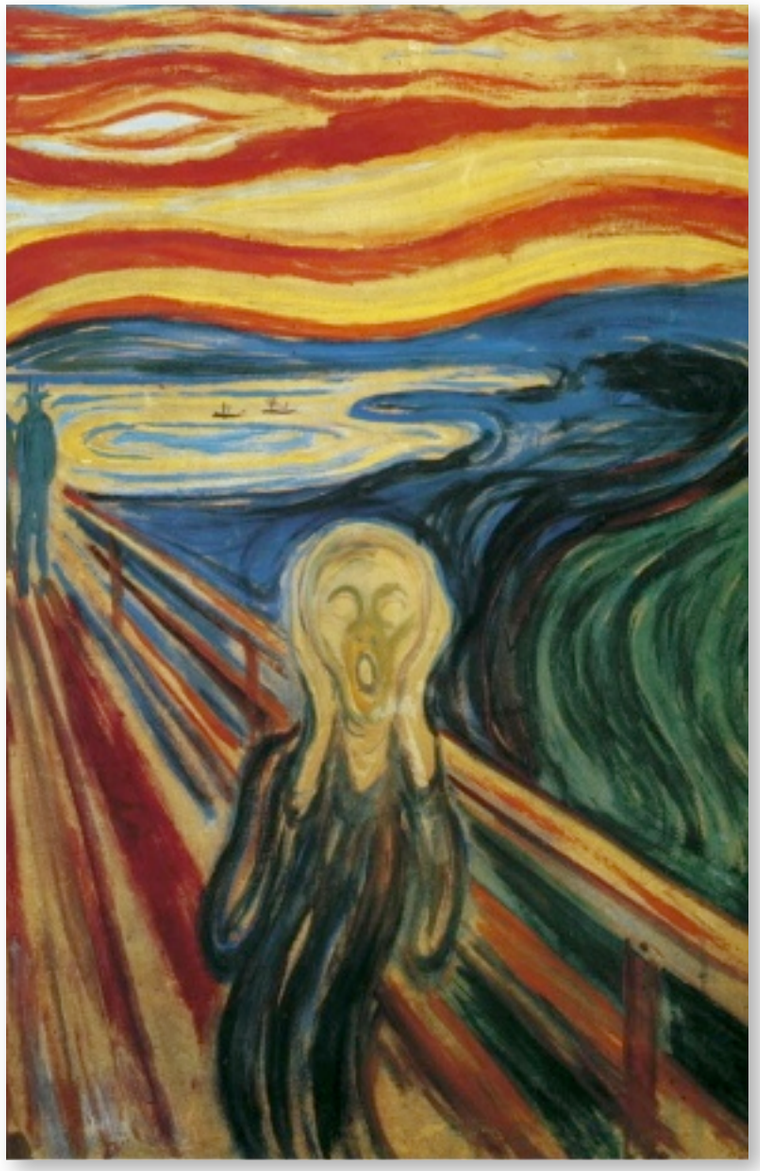
- 1 gray = 1 joule of x-rays, γ-rays, or electrons (β) absorbed in 1 kilogram of tissue
  - raises temperature by 0.0004°F
  - neutrons (n) are 10 times more damaging
  - α particles are 20 times more damaging
  - 1 sievert = does equivalent of 1 gray of x-rays
    - 1 Sv = 100 rem

How do radioactive particles interact with biological tissue?

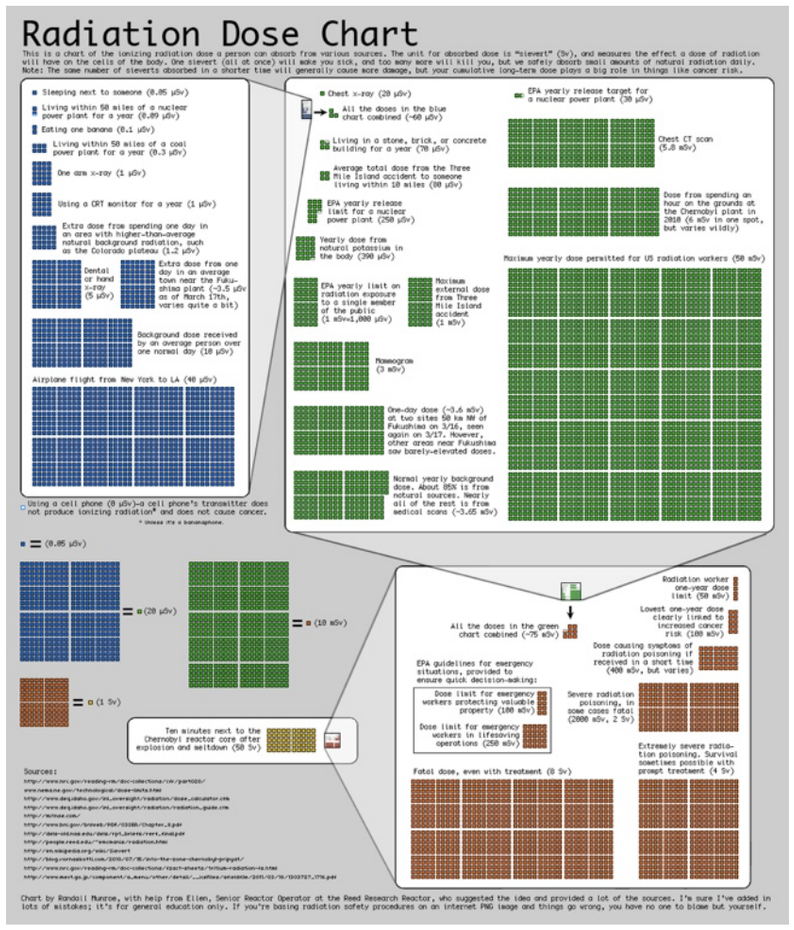
- Bonds break
- Reactive radicals (ions) form; can attack DNA or other molecules
- In low dosage, cells repair damage
- Higher dosage leads to cell death or possibly cancer
- Very high dosage disrupts bone marrow
- Extremely high dosage incapacitates and leads to death within hours (> 8 Sv)

Important number

3 Sv = LD50



Common daily dosages



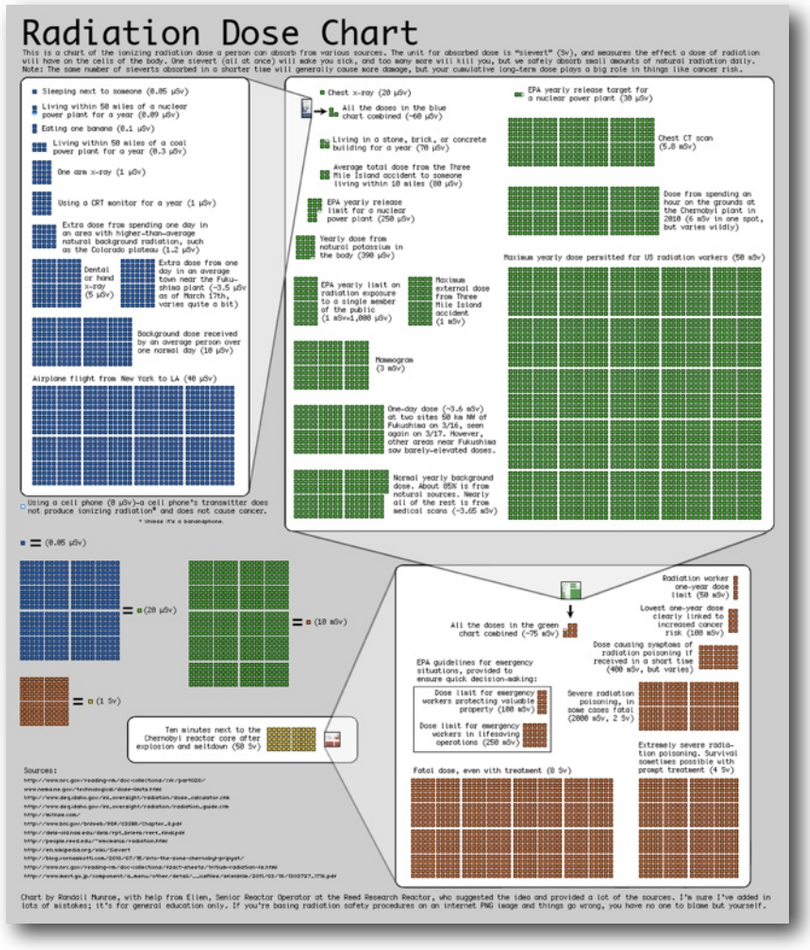
http://xkcd.com/radiation/

- 1 banana (0.1 μSv)
- dental x-ray (5 μSv)
- a day in Colorado (1.2 μSv > normal)

extra dose per day in town near Fukushima (~4 μSv)

- a normal day (10 μSv)
- flight NY to LA (40 μSv)

Common annual dosages



- potassium in body (390 μSv)
- EPA limit to public (1 mSv)

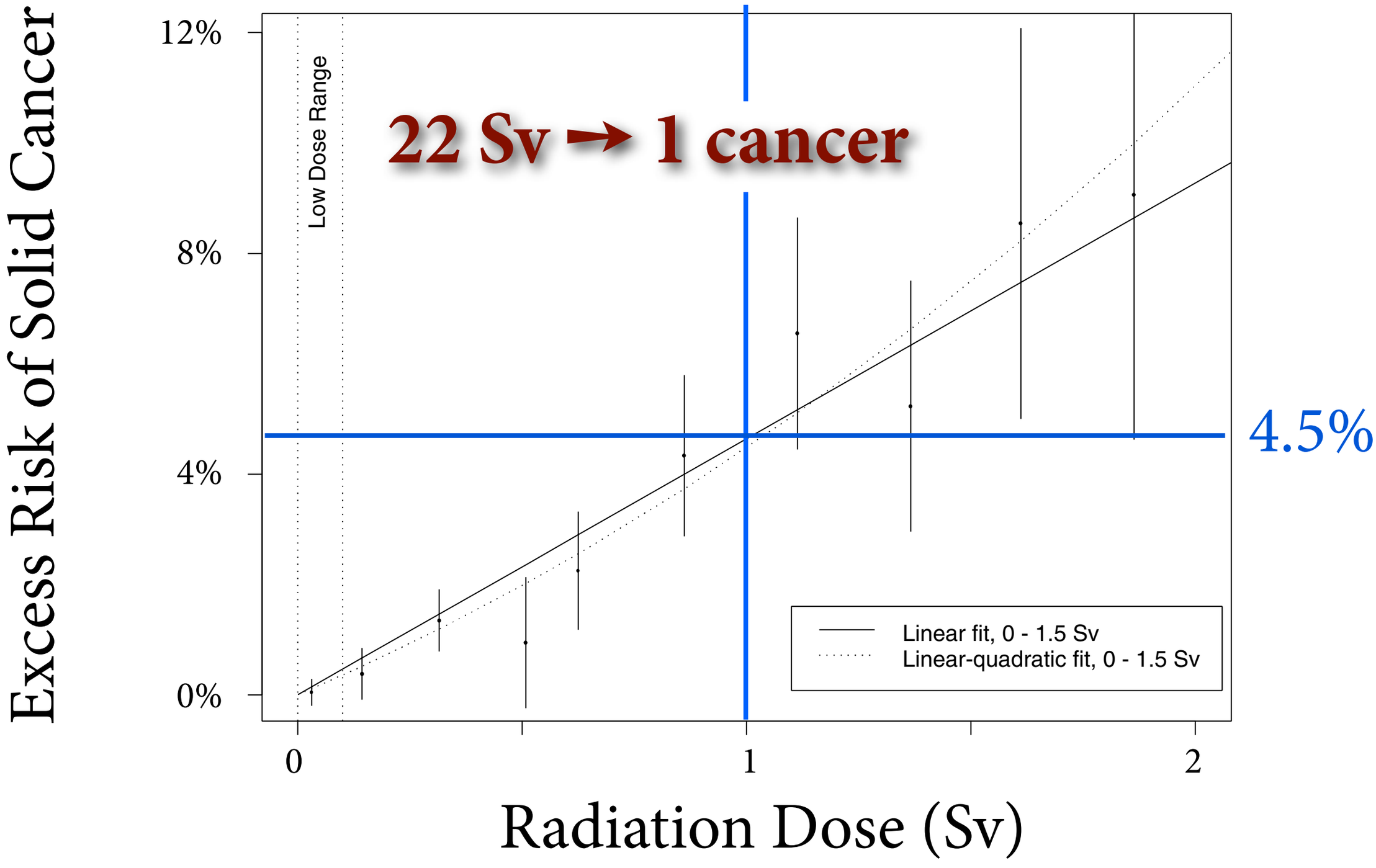
maximum external dose from Three Mile Island (1 mSv)

- mammogram (3 mSv)
- normal yearly dose (3.65 mSv)
- chest CT scan (5.8 mSv)

http://xkcd.com/radiation/

Linear model

BEIR VII



Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII – Phase 2 (2006)

http://www.nap.edu/

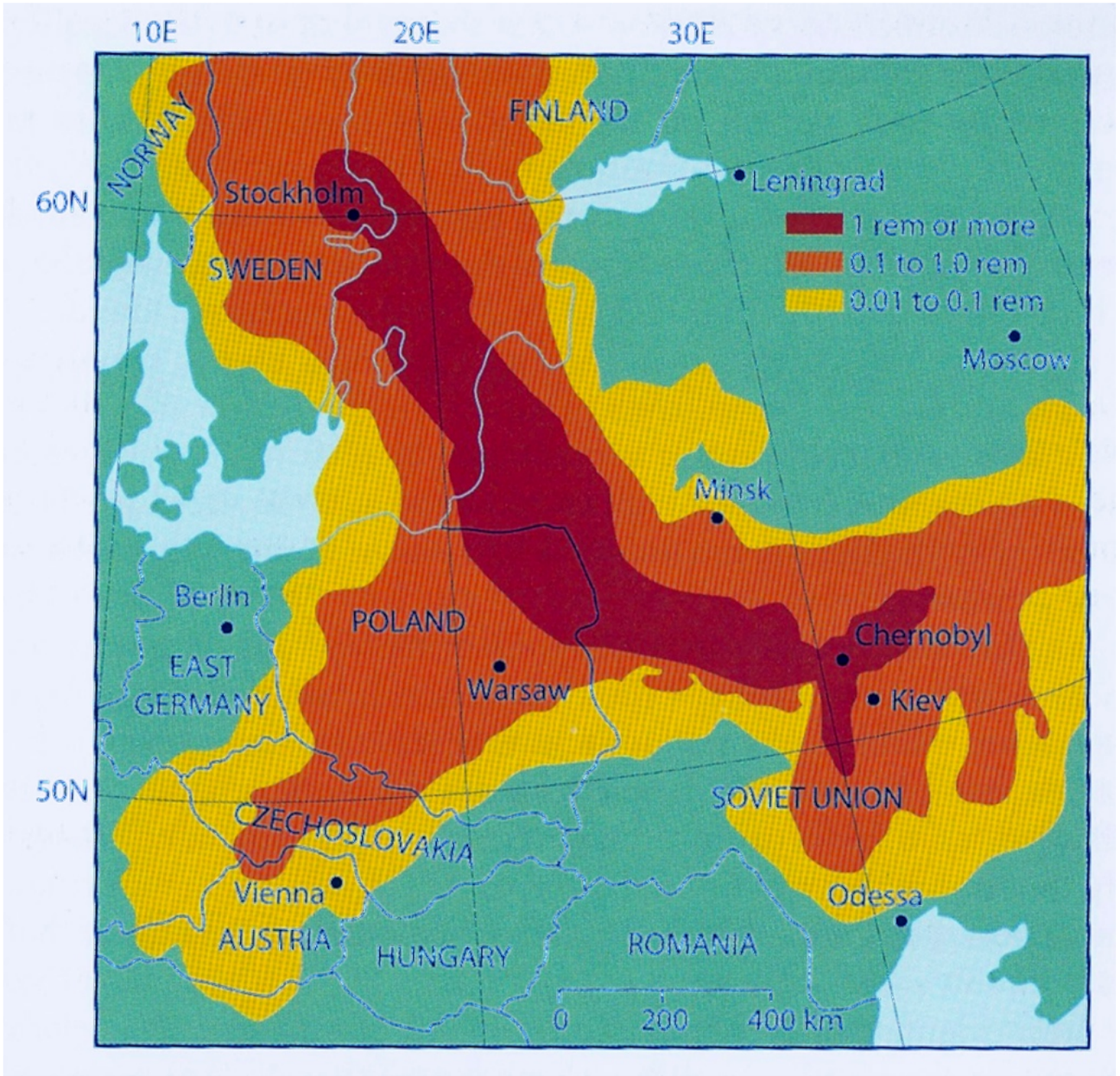
Three Mile Island (1979)

- Pumps supplying cooling water failed
- Valve to backup pump was accidentally left closed
- Control rods were inserted, but decaying fission fragments continued heating
- Operator turned off emergency core cooling because he thought the reactor was full of water
- 1/3 of core melted
- Some radioactive steam vented; expected cancers from leakage: 1

http://www.eoearth.org/files/122001_122100/122018/300px-Three_mile_island.jpg

Chernobyl (1986)

- Explosion and fire
- Dozens of firefighters exposed to several sieverts; die of radiation sickness
- IAEA estimates 0.6 MSv total exposure ☞ 10,000–24,000 cancers worldwide among 100 million people exposed
- Normal cancers: 20,000,000
- Increased thyroid cancer in Ukraine, especially among children (~4×)

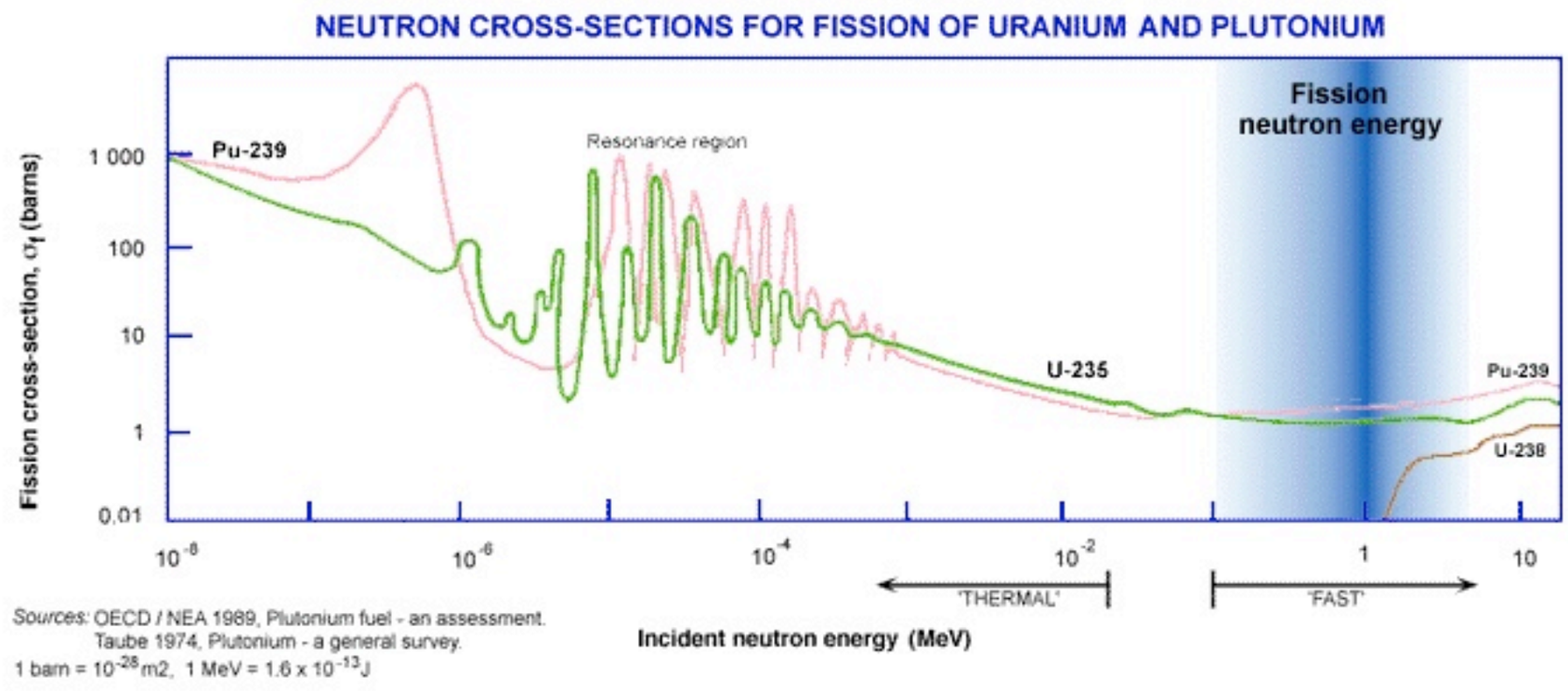


0.1 mSv >1 mSv >10 mSv

Howe et al., Journal of the National Cancer Institute, 5 July 2006;
Frank von Hippel, New York Times, 23 March 2011

Thermal neutrons

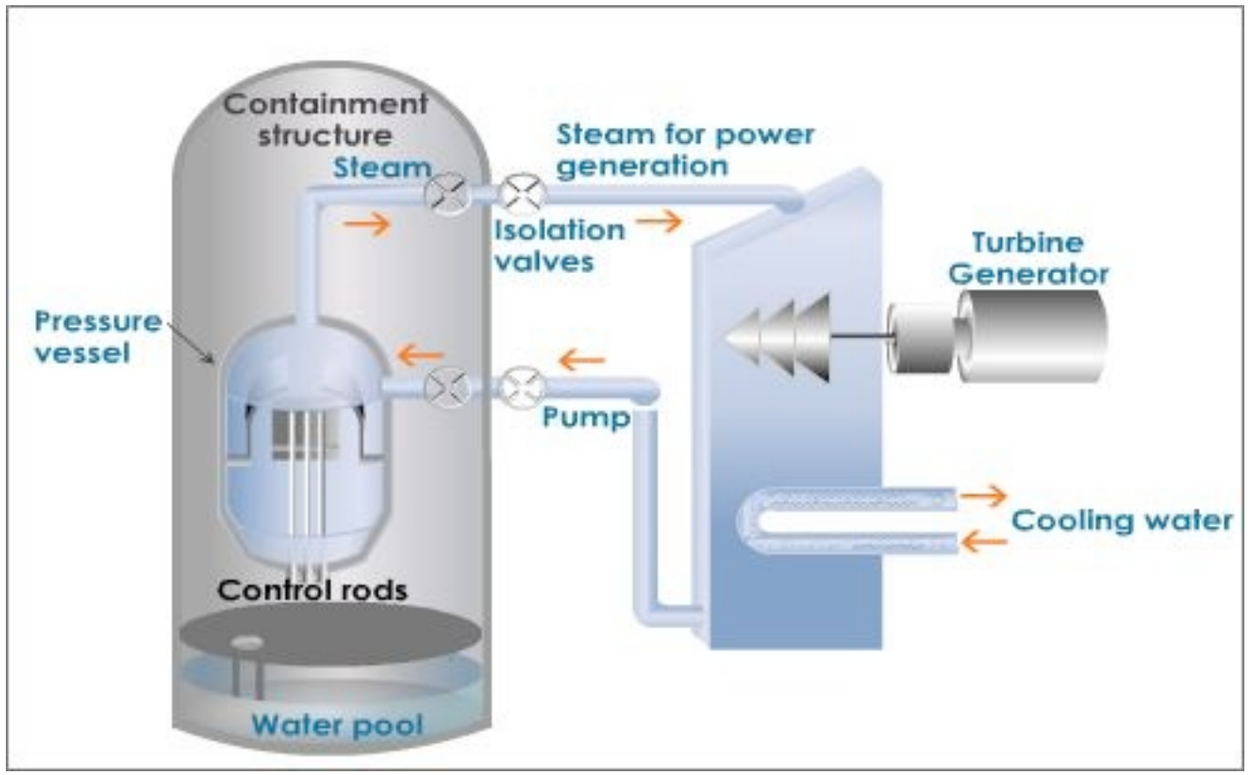
- U^{238} only absorbs fast neutrons
- U^{235} and Pu^{239} absorb slow (thermal) neutrons



- When U^{235} absorbs a neutron and then fissions, ~2 neutrons come out
- If 1 of those is absorbed by another U^{235} there is a sustained chain reaction

How does a reactor work?

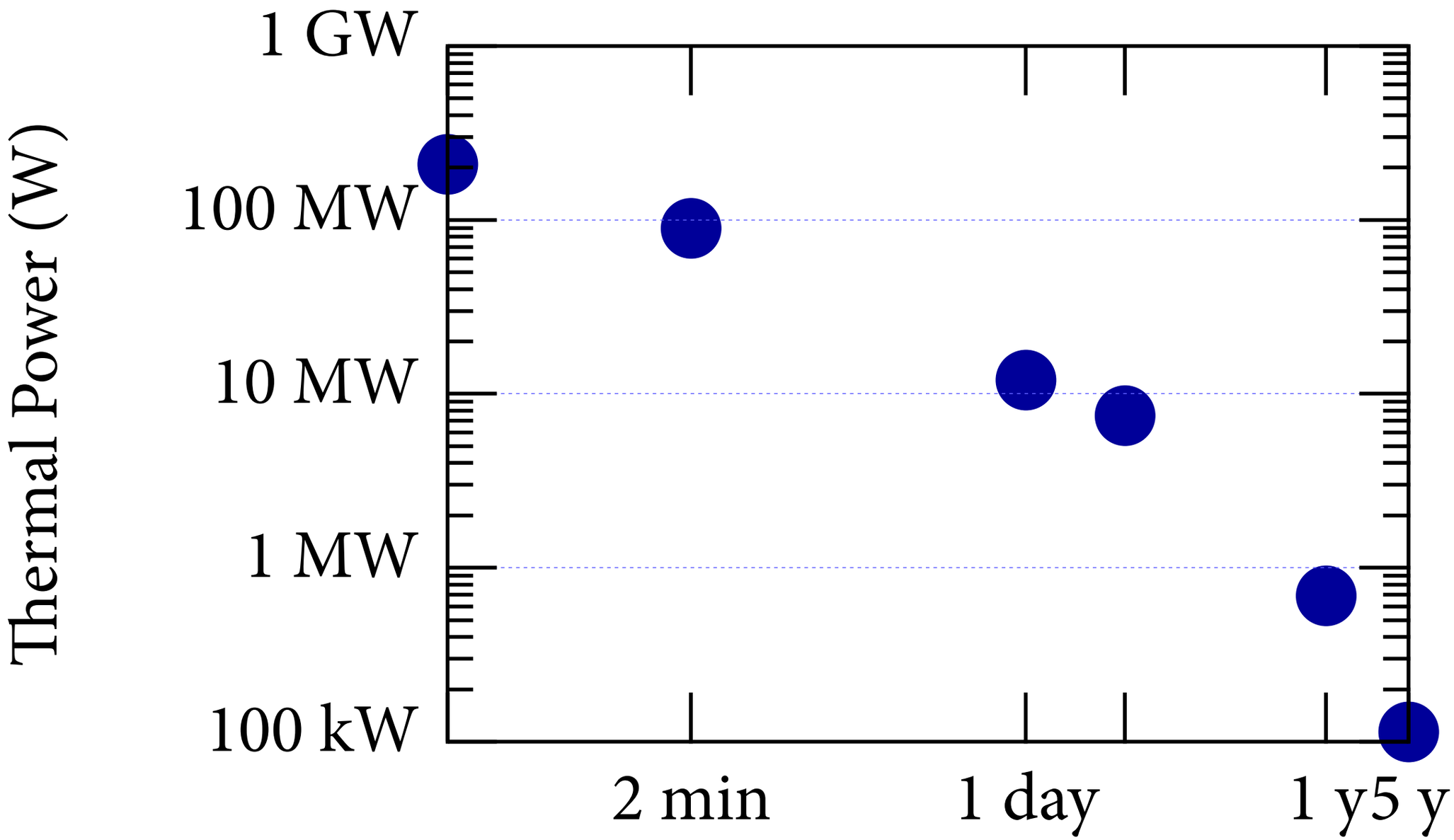
- Water moderates neutrons (slows them down)
- Boils to produce steam to run turbine
- Control rods adjust neutron flux
- After shutdown, need cooling



http://image.wistatutor.com/content/fission-and-fusion/boiling-water-nuclear-reactor.jpeg

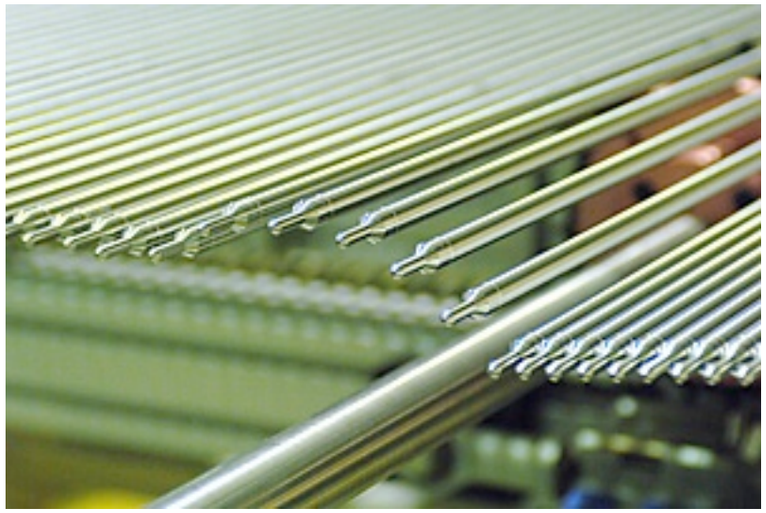
Spent fuel rod cooling

3 GW reactor



Src: NC State Nuclear Engr. 3/23/11

Spent fuel rods



- Stored in water to cool and suppress radioactivity
- Transfer takes place to pool *above* top of reactor vessel
- Stored for years as fission fragments decay
- $Zr + 2\ H_2O \longrightarrow ZrO_2 + 2\ H_2$ + heat

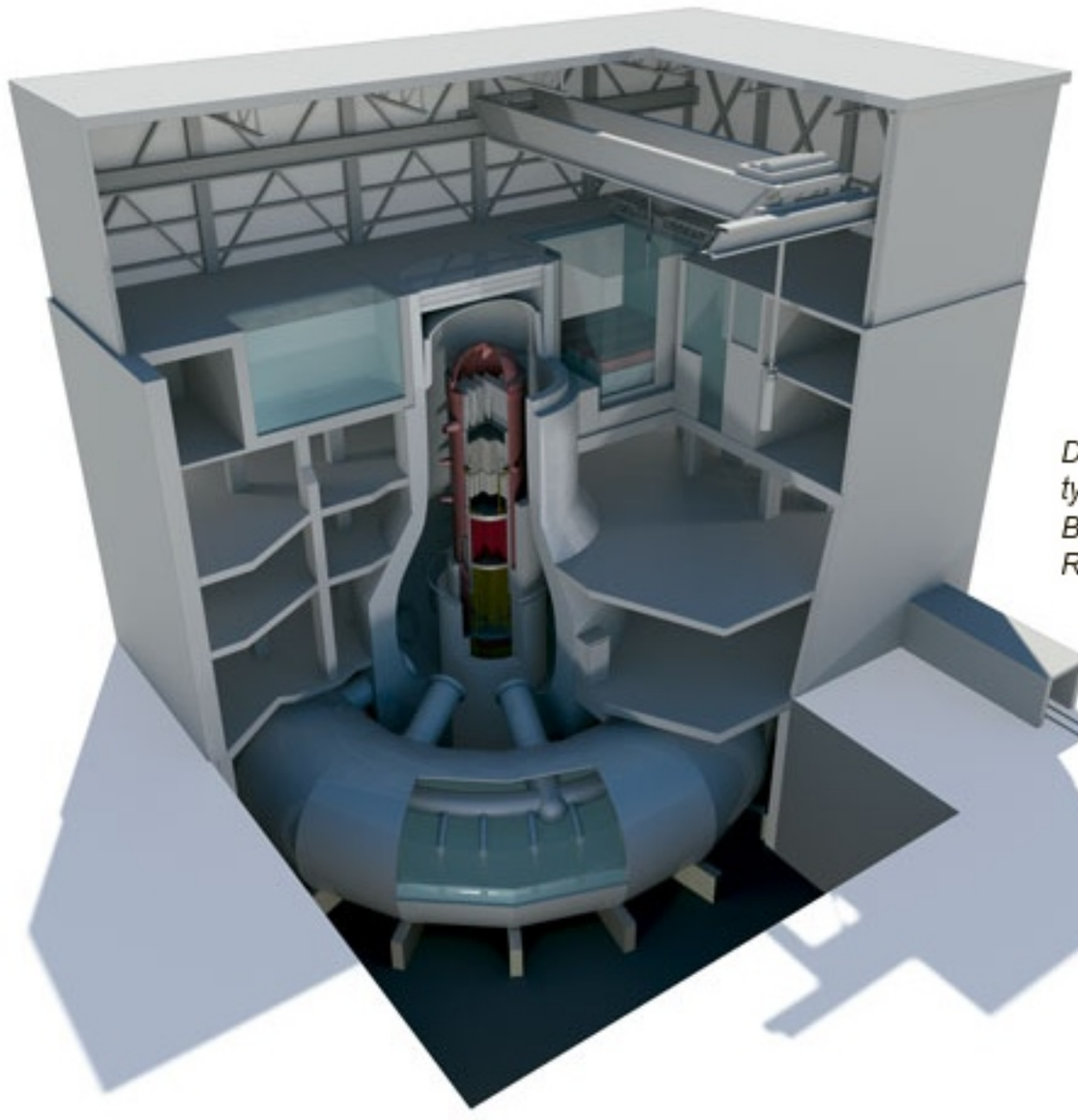
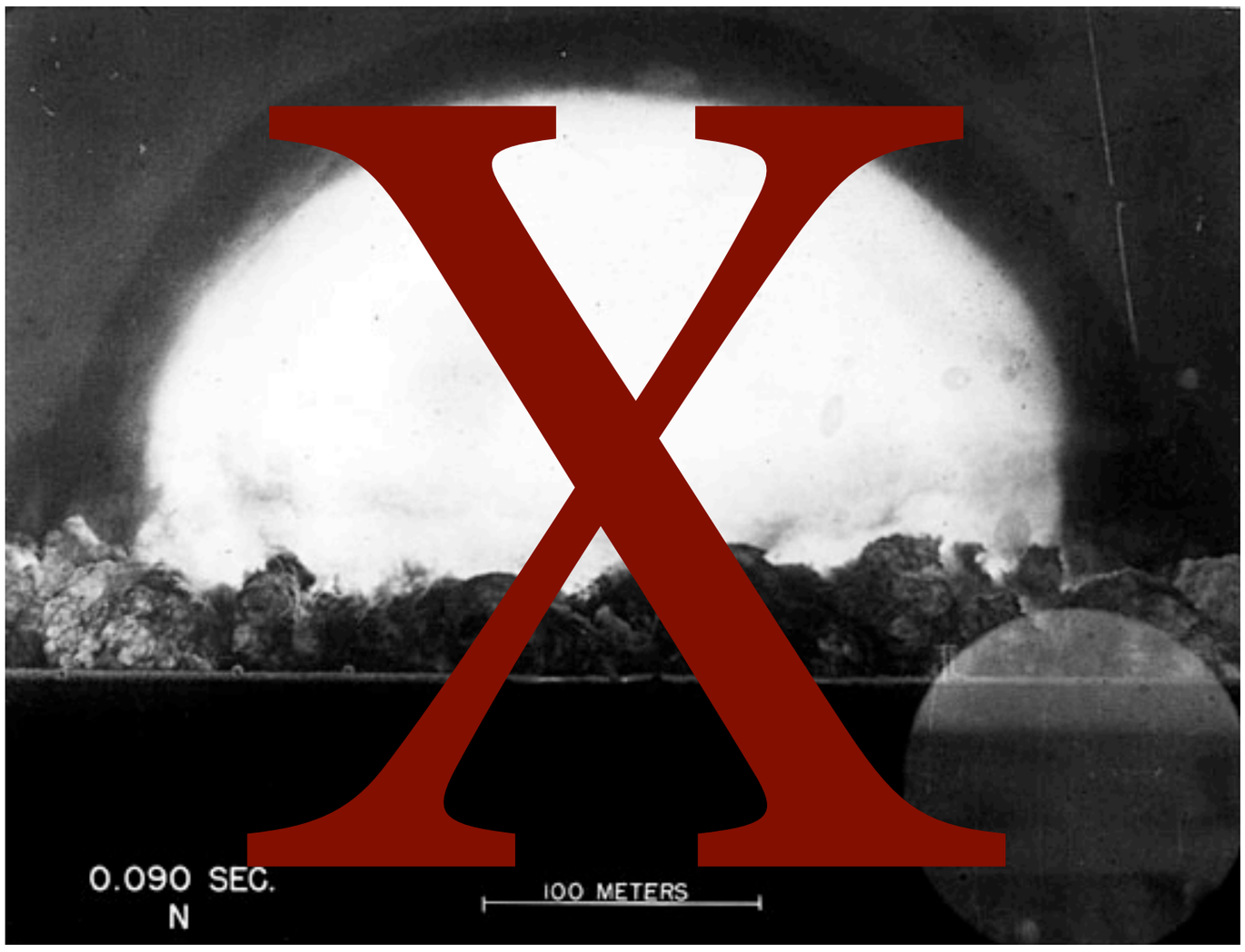


Diagram of a typical Mark I Boiling Water Reactor

New York Times, 19 March 2011

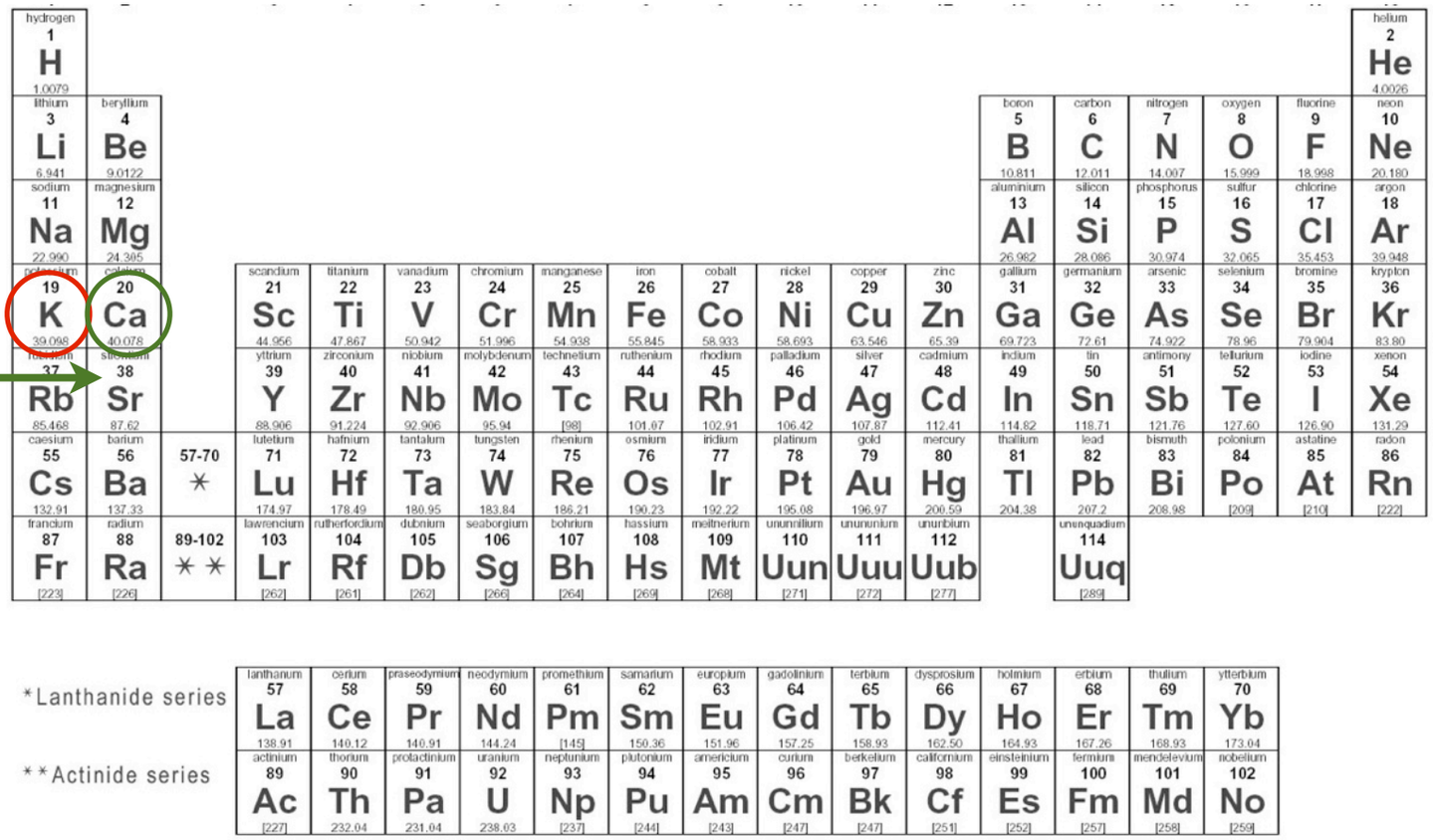
Can a reactor explode like a nuclear bomb?

- No — too many of the neutrons are absorbed by U^{238} to permit reaction to run away explosively
- A uranium bomb requires enrichment of U^{235} fraction to ~95%



Dangerous species

I^{131}	8.14 days	thyroid those near Fukushima should take iodine salts
Sr^{90}	29.9 years	like calcium
Cs^{137}	30.1 years	like potassium

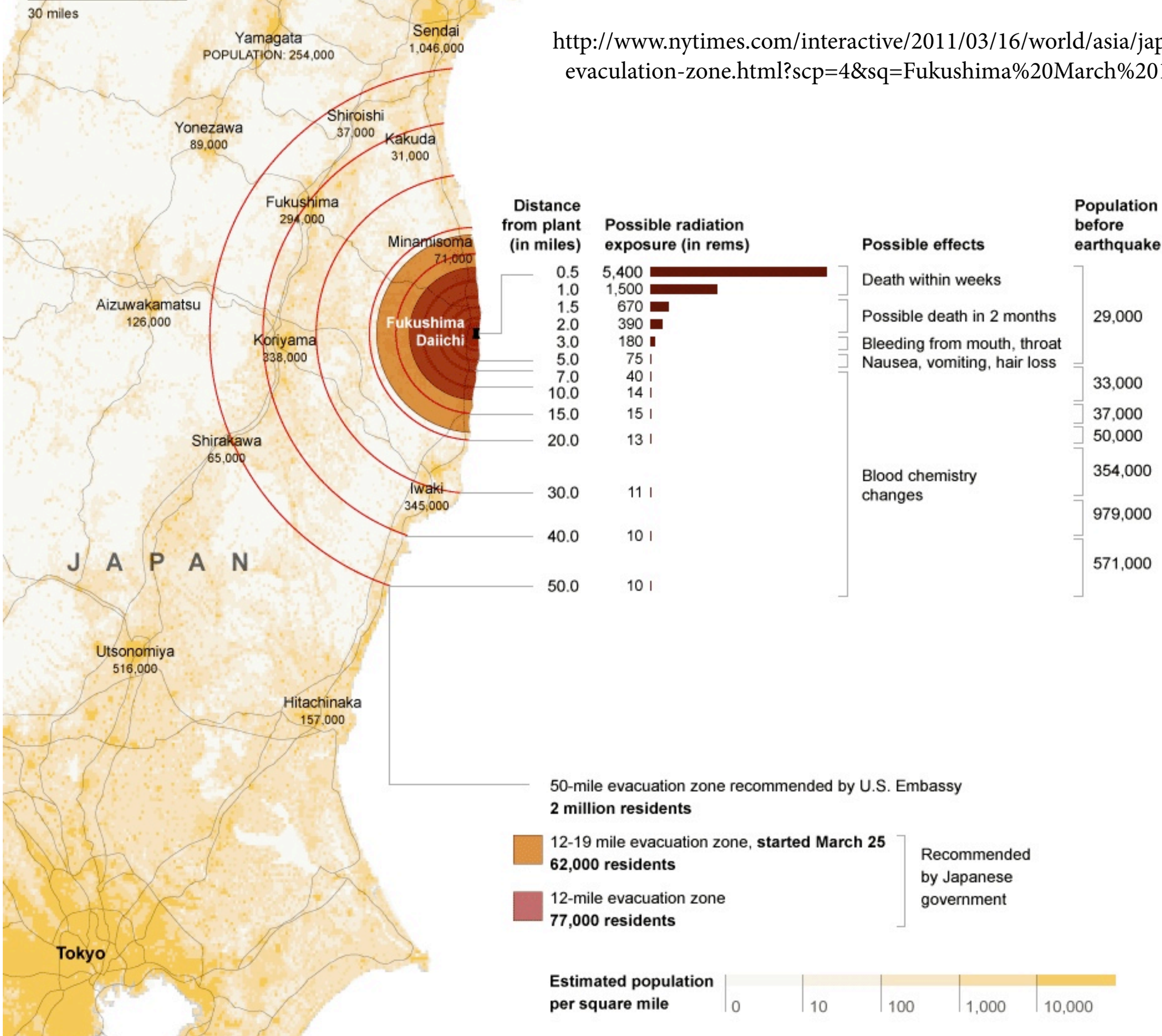


Observed radiation levels

- 3/15, Main gate, Fukushima Daiichi plant: 11.9 mSv/hr @ 9:00, down to 0.6 mSv/hr @ 15:30
- 3/17, 0.338 mSv/hr @ 5:00
- *Los Angeles Times* (3/18): Xe^{133} detected in Sacramento, according to the EPA. Dose: one-millionth normal background.
- 3/19, Tokyo tap water: 1.5 becquerels/kg of I^{131}. Tolerable limit: 300 becquerels/kg.
- 3/23, *Bulletin of the Atomic* Scientists: Tokyo tap water: 210 becquerels/kg of I^{131}, unsafe for babies
- 3/24, *Bulletin of the Atomic Scientists*: workers stepped in highly radioactive water; received beta ray burns; dose of ~0.18 Sv or more.

http://www.earthlyissues.com/japannuclear.htm

http://www.nytimes.com/interactive/2011/03/16/world/asia/japan-nuclear-evaculation-zone.html?scp=4&sq=Fukushima%20March%2016&st=cse/

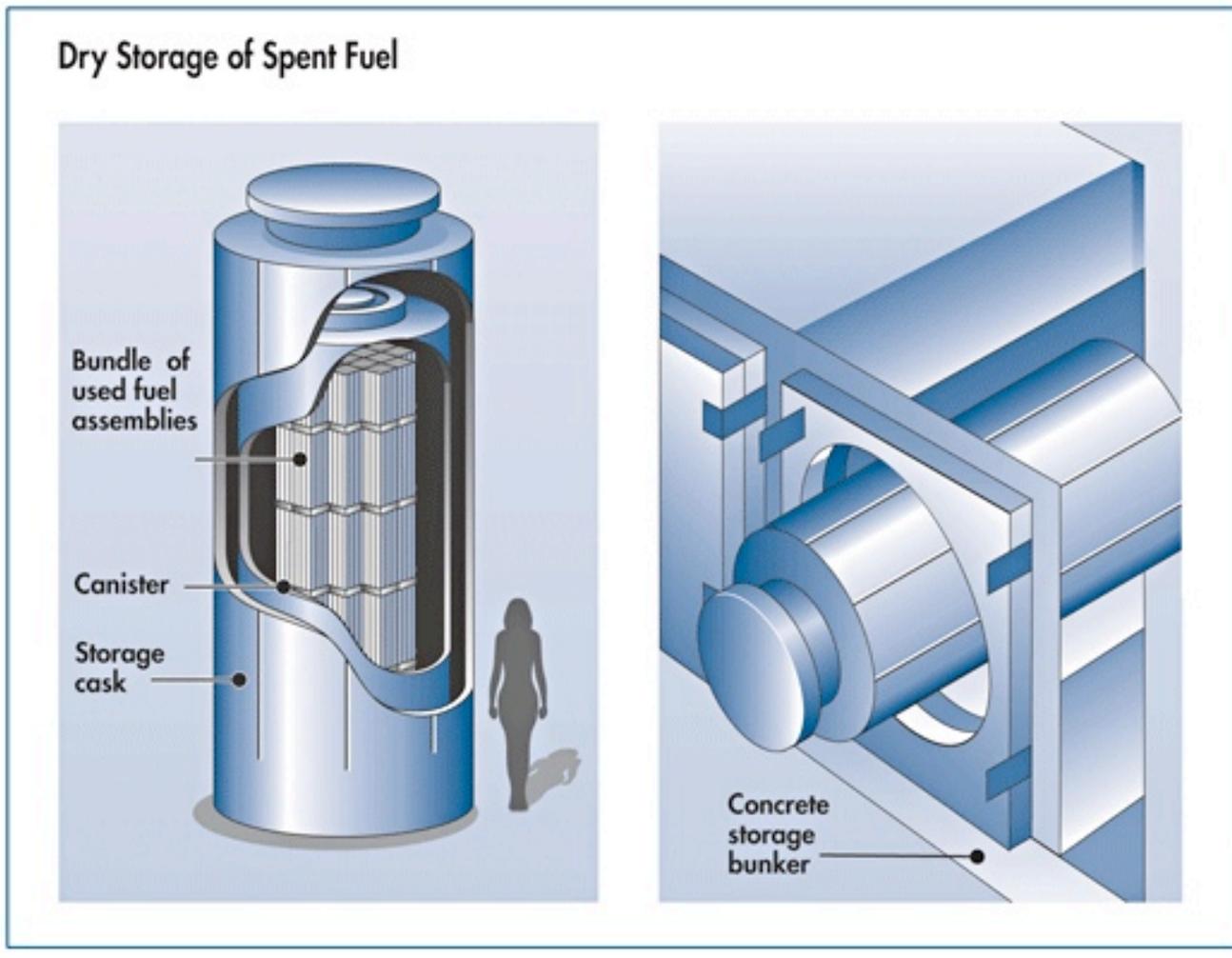


Risks

- Chernobyl: 10,000 – 24,000 cancer deaths
- Coal: 10,000 deaths/year in the United States
- Traffic accidents: 24,474 deaths in US in 2009; 2,011,000 injured; 1.13 fatalities per 100 million miles traveled
- Air is 12x safer than train *per passenger mile*, and 62x safer than car; air is 3x more dangerous than car and 30x more dangerous than bus *per passenger trip*

Prudence

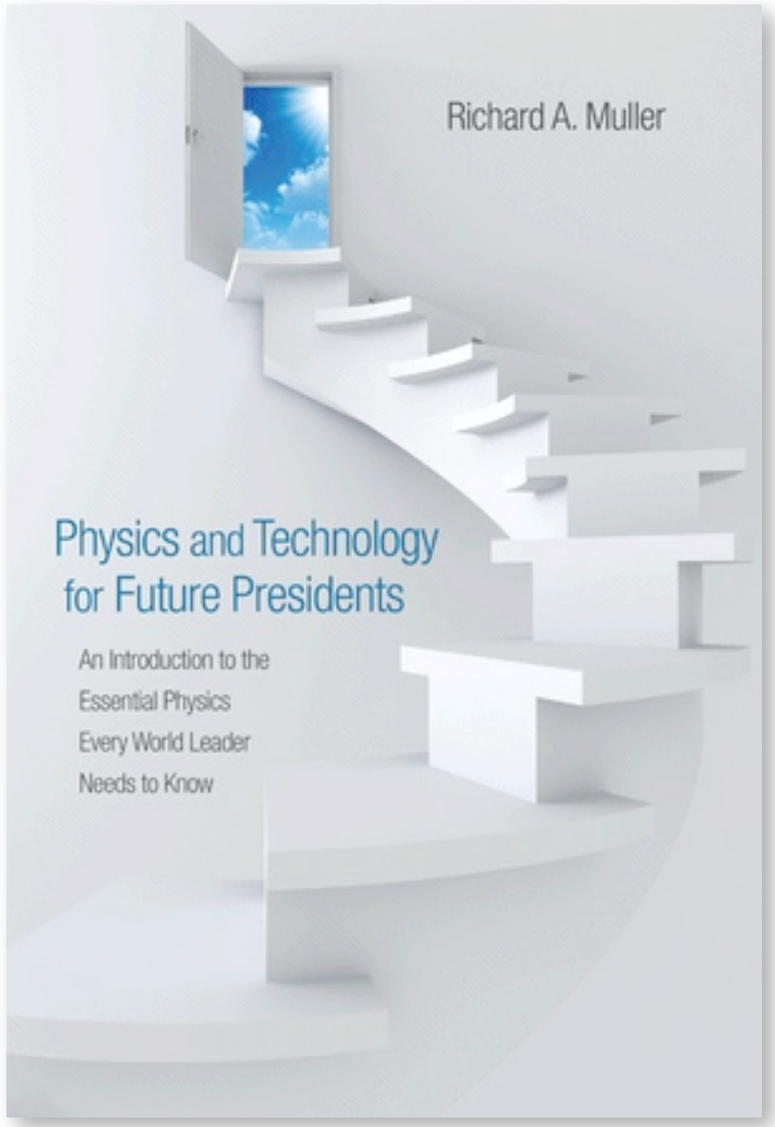
- Dry cask storage (NRC Commissioner Gregory Jaczko; Union of Concerned Scientists)
- Filtered ventilation of outer containment
- More separation between the Nuclear Regulatory Commission and industry
- Permanent repository?



U.S. NRC

More information

- http://www.ne.ncsu.edu/
- http://www.nytimes.com/
- http://www.jaif.or.jp/english/
- http://armscontrolwonk.com/
- http://www.thebulletin.org/
- *Physics and Technology for Future Presidents*, Richard A. Muller (Princeton, 2010)



Radiation effects

Dose (Gy)	Molecular Processes	Cultured Human Cells	Humans
0.001		Yearly background dose	
0.01	No measurable effects	No measurable effects	Possible increased risk of childhood cancer after in utero irradiation
0.1	No measurable effects	Induction of mutations and malignant transformation	Chromosome aberrations in peripheral blood lymphocytes
0.5	Decrease in nuclear phosphorylation in some cells	Cytogenetic changes	Interphase death in peripheral lymphocytes; increased cancer risk
1	Rate of DNA synthesis shows transient reduction	Growth delay, but greater than 95% survival in cultured cells	Slight acute illness; 100% survival; increased long term cancer risk
5		10% survival	Extreme acute illness; ~50% survival
10	Transfer of RNA to cytoplasm transiently interrupted	1% survival	100% lethal
100	Energy metabolism decreased; DNA repair capacity unaffected	Immediate (interphase) death in cultured cells	CNS and cardiovascular system collapse; immediate death
1000	Membrane function failure; end of coherent metabolism	Instantaneous death	Probably instantaneous death